

**UNITED STATES AIR FORCE
ARMSTRONG LABORATORY**

**Physiological Effects of Chemical
Protective Garments During Exercise
and Heat Stress**

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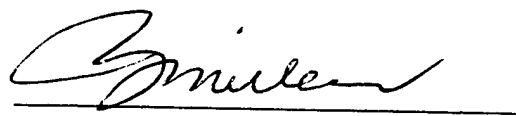
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13. ABSTRACT (Maximum 200 words) The present study was designed to examine the effect of protective garments, with a range of insulation and permeability characteristics, on changes in physiological parameters during exercise and on heat balance in warm and hot environments. Dressed in the U.S. Army Battle Dress Uniform (BDU), the U.S. Army Chemical Defense Ensemble (CDE), a butyl rubber Toxic Agent Protective (TAP) suit, and the CDE covered by a two-piece vinyl rainsuit (RAIN), volunteers walked on a treadmill at a workrate of 481 ± 35.4 watts. Environmental conditions for hot experiments were 38/26/43 degrees Celsius, Tdb/Twb/Tbg, and for warm trials, 29/24/34 degrees Celsius. The subjects exercised until reaching 39 degrees Celsius Tre, max HR, or volitional fatigue. Pre- and post-experiment nude and clothed weights were measured and used to calculate sweat production (SP) and sweat loss (SL). TAP and RAIN had significantly shorter tolerance times than the CDE or BDU in both warm and hot environments. For the same suit, tolerance time was reduced in the hot environment compared to warm conditions. Sweat production was significantly increased as suits became less permeable and as the temperature increased from warm to hot. Sweat evaporation (SE) was affected significantly only by the ensemble. Body heat storage occurred at a lower rate than predicted, especially in the hot environments where Tdb was greater and Tsk which should make radiative heat loss negligible and in trials where individuals wore impermeable ensembles (TAP and RAIN) which should have blocked evaporative heat loss.				
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PHYSIOLOGICAL EFFECTS OF CHEMICAL PROTECTIVE GARMENTS DURING EXERCISE AND HEAT STRESS

INTRODUCTION

Selected personnel in both military and civilian industrial settings are required to wear protective clothing while they are performing work in a range of climatic conditions. Protective clothing must, by definition, be made of a material which is partially to fully impermeable to moisture and vapor hazards in order to provide effective protection from liquid and vapor hazards. An additional goal for these garment systems is to maintain the wearer's body temperature within acceptable levels (17). Unfortunately, in most cases, wearing protective clothing ensembles significantly increases the level of physiological heat stress experienced for a given set of environmental conditions to a level equivalent to adding 3-10 °C to the wet bulb globe temperature (WBGT) (12,18). Considering the perceptual responses of the wearer, these estimates may indeed be conservative.

Under mild environmental conditions and work rates, heat production can be balanced by heat loss through radiation and convection. (14). However, when clothing is added, a heat transfer barrier is formed between the skin and the environment. This resistance to the normal flux of heat away from the body may be empirically partitioned. The thermal insulation (clo) of the material interferes with the dry heat loss per unit of surface area for each degree of temperature difference between the skin and the ambient temperature. While the evaporative resistance (im) of the garment determines the evaporative heat loss for each mmHg vapor pressure difference between the vapor pressure of the skin saturated with sweat and the ambient vapor pressure (5,6,11). When environmental temperature rises above body temperature, thus reducing possible heat loss through radiation and convection, heat balance can be achieved only through evaporation. At this point the water vapor permeability characteristics of the clothing assumes primary importance (12). Although sweat production in protective clothing often exceeds one liter per hour (2), as clothing layers increase and permeability to water vapor decreases, only a fraction of the produced sweat evaporates at the skin and provides efficient cooling (5). Therefore, hard work in impermeable suits at temperatures above approximately 80 °F greatly reduces work capacity and can cause heat stress (2). Under hot environmental conditions, heat stress symptoms (high rectal temperature and heart rate) are apparent much earlier when vapor barrier clothing is worn (12,18).

Static, bench-level evaluations may be made to estimate the rates of dry heat transfer and water vapor transfer across fabrics with a variety of techniques (17). However, when the fabric is configured and worn as an ensemble the routes of energy transfer

become much more dynamic. This phenomenon is commonly attributed to non-uniform fabric/body-surface spacing and the number and type of ensemble closures. These factors are combined with the "pumping" effect of the kinematic motion of the body in which varying rates of heat exchange take place through garment closures as well as through the fabric itself. Consequently, clothing insulation (i_{cl}) is higher while the permeability (i_m) value is lower when measured on a manikin, than is the case with moving human subjects (9,19). Conventional heat balance equations may not accommodate these additional factors. Values for body heat storage obtained in the laboratory are often below those computed using standard heat balance equations which incorporate static copper manikin values for i_m and i_{cl} (4). Moreover, computer modeling (21) of scenarios involving exercising humans in protective clothing, which is often based on static measurements and equations, may not accurately depict the complex effects of clothing systems on heat balance, especially when multiple clothing layers are worn. Such factors as sweat evaporation and "pumping" may be therefore underestimated in models.

In the present study, we examined the effects of protective garments (with a range of insulation and permeability characteristics) on changes in selected physiological parameters during exercise. We characterized these effects on heat balance and subjective psychological responses in both warm and hot environments. An enhanced data base from human trials providing objective physiological measures on clothing performance can be used to validate and improve computer models (17).

METHODS

The following protective clothing ensembles were worn in this study: the two-piece U.S. Army Battle Dress Uniform (BDU), ($i_{cl}=1.48$, $i_m/i_{cl}=0.26$), the two-piece charcoal foam U.S. Army Chemical Defense Ensemble (CDE), ($i_{cl}=2.50$, $i_m/i_{cl}=0.15$), a one-piece butyl rubber Toxic Agent Protective suit (TAP) ($i_{cl}=2.05$, $i_m/i_{cl}=0.04$) plus a layer of SARAN wrap over and around all major ensemble closures.

All subjects wore all ensembles in a repeated measures experimental design. The only exception was that the BDU trial always took place after the CDE trial in warm conditions. Subjects wore the MCU-2/P chemical protective mask, filter, and M-61/A butyl rubber hood with all ensembles. Cotton T-shirt and underwear, and chemical protective butyl rubber gloves with cotton liners were also worn. Subjects walked in tennis shoes rather than in chemical protective overboots to avoid injury. Wearing the battle dress uniform (BDU) trial in warm conditions, subjects exercised the same amount of time as they had in the chemical defense ensemble (CDE); pilot studies had indicated that subjects' heat storage in the BDU reached an equilibrium condition at approximately this point. Therefore the BDU trial data was used

in the 30 min comparisons only.

Human volunteer subjects (n=9, 1 female and 8 males) with an average age of 35 ± 5.9 years, weight of 78.0 ± 104 kg, and height of 175 ± 4.3 cm, having signed an informed consent form, participated in the study. Volunteers walked on an inclined treadmill at a work rate, measured by open circuit spirometry, of 481 ± 35.4 Watts which was $41.1 \pm 2.2\%$ of the subjects' average $\dot{V}O_2$ max of 44.6 ± 3.3 ml O_2 /kg/min. The environmental chamber conditions for the hot experiments were $38/26/43$ °C, $T_{db}/T_{wb}/T_{bg}$ respectively and for the warm trials were $29/24/34$ °C. Ambient vapor pressure was similar for all trials (19 Torr), while windspeed was measured at less than .5 m/sec.

Heart rate (HR) was monitored with a Transkinetics telemetry system. YSI thermistors, were affixed to skin at the chest, forearm, calf and thigh using a surgical grade of water resistant tape. Mean skin temperature (T_{sk}) was calculated as .5 chest + .14 forearm + .36 calf (3). Core temperature (T_{re}) was measured using a rectal thermistor inserted 10 cm past the anal sphincter. Body heat storage (HS) was calculated using a weighing of .2 mean skin temperature (T_{sk}) + .8 T_{re} . Variables of HS, T_{re} , T_{sk} , and heart rate were monitored continuously and recorded every 30 seconds in a computerized data acquisition system while the subjects exercised until reaching tolerance limits of 39 °C T_{re} , max HR, or volitional fatigue. Pre and post experiment nude and clothed weights were measured to .01 kg and used to calculate sweat production (SP), sweat loss (SL) (evaporation + drippage), and SL/SP (% of sweat produced which was evaporated). Subjective measures of Thermal Comfort (TC) (24) and Rated Perceived Exertion (RPE) (1) were recorded every 5 minutes.

A further analysis was undertaken to explore the specific partitioning of heat flux and energy balance during the active wear of a fully impermeable protective ensemble TAP suit. Heat balance was either calculated from physiological measures of metabolic rate, evaporative loss, and heat storage using standard equations (7) or predicted with an integrative physiological computer model (21). Radiative and convective heat loss was determined arithmetically. The final values for tolerance time, HR, T_{re} , T_{sk} , SP and SE were analyzed using a 3 way ANOVA (suit, subject, temperature) followed by a Duncan's multiple range post hoc test to determine individual differences.

RESULTS

Both the type of ensemble and the environmental temperature had a significant effect of tolerance time (Table 1). Not unexpectedly, ensembles with high insulation and lower permeability (TAP and RAIN) had significantly shorter tolerance times than the CDE or BDU in both warm and hot environments. While for the same suit, tolerance time was further reduced in the

hot environment compared to warm conditions. As mentioned previously, the warm BDU tests were stopped by the investigator. Therefore, these final values are not included in this analysis. In examining values for final mean skin temperature, there was a significant interaction of temperature and ensemble type, meaning that the magnitude of hot-warm differences was not the same for all ensembles. There were also significant differences between ensemble types within a temperature and between temperatures as indicated in Table 1. SP was significantly increased as suits became less permeable and as the temperature increased from warm to hot. Sweat evaporation (SE) was affected significantly only by the ensemble worn. Tolerance time was defined as $T_{re} + 39.0^{\circ}\text{C}$ or max HR, in the warm CDE case or equal to the BDU trials, and most subjects were close to both at the end of the trials. Therefore, final values for T_{re} and HR were not affected by either suit or temperature.

The trials in the more stressful ensembles, TAP and RAIN, lasted approximately 30 min in the hot environment; therefore, an additional 3-way analysis of variance (ANOVA) of the data was conducted on the change in physiological variables at the 30 min point. As depicted in Figs. 1, 2, and 3, by the 30 min point there were significant temperature by suit interactions for the delta increases in T_{sk} , T_{re} , and HS. Not surprisingly, this data indicates that the effect of environmental temperature resulted in greater increases in T_{sk} for TAP and RAIN than for BDU and CDE. For T_{re} and HS, TAP response was obviously different from the other suits. Variables of HR, TC, and RPE were significantly altered at 30 min by type of suit and environmental temperature, but there was no interaction effect (Fig 4, 5, 6). Comparisons of the results from the physiological studies of the TAP suit versus the results of computer modeling of an impermeable suit are found in Table 2.

DISCUSSION

Not unexpectedly, a significant difference in the magnitude of change in physiological variables between warm and hot environments was observed after only 30 min of work across all ensembles. There was a significant suit effect for all variables and an effect of temperature for HR, RPE, and TC. The difference in heart rate between hot and warm conditions for each ensemble remained constant, the effect being an increase of 7 bpm in hot over warm conditions. This relationship is very similar to another study where it was found that there is approximately a rise of 1 bpm for each 1°C rise in the ambient temperature (23). There were also two situations where the suit and temperature effects interacted. The increases in variables HS, T_{re} , T_{sk} , over time caused by the environmental temperature was greater for the impermeable ensembles than for the more permeable ones; i.e., the difference (delta) between values measured in warm and hot conditions increased more across time for impermeable suits. The

overall magnitude of hot-warm differences for each ensemble was significant; thus, clothing characteristics obviously caused a difference in the physiological response to environmental temperature. As a specific example, for HS, T_{re} , T_{sk} , in the hot environment the 30 min delta values were higher for TAP than for the RAIN suit. In the warm environment the physiological stress effects for the RAIN suit were higher than for the TAP. Although both suits are virtually impermeable, this variance illustrates the probable impact of the higher insulative value of the RAIN suit on radiative heat transfer; preventing some heat gain in the hot environment while preventing heat loss in the warm environment.

The higher environmental temperature had a dramatic effect on tolerance time when BDUs only were worn. In warm environmental conditions subjects reached equilibrium in rectal temperature and were therefore stopped by the investigator after the same amount of time they had walked in the CDE; at that point mean T_{re} was $\sim 38.2^{\circ}\text{C}$. In the hot environment, tolerance time in BDUs was only six minutes longer than in the much more insulative CDE. This effect confirms that loss of radiative and convective avenues of cooling when ambient temperature exceeds body temperature, raises body heat storage levels even for relatively lightweight clothing. More importantly, it emphasizes the likely contribution of the mask, hood, and gloves, to body heat storage under these more stressful environments.

Sweat production increased in the hot environment when compared to the warm environment for each ensemble, probably due to the higher T_{sk} (15); It increased as the suit i_m decreased. Sweat evaporation stayed approximately the same for each suit regardless of temperature, but there was a significant difference in evaporation between suit types. It appears likely that there is a maximal evaporative capacity for each suit (4,11); after that point is reached, increasing skin or environmental temperature has no effect. In the permeable suits the number of subjects stopping exercise volitionally (due to fatigue rather than when they reached a physiological limit) increased, emphasizing the impact the physiological stress has on the motivation necessary for perseverance in work duration and effort.

Previous studies have concluded that when T_{re} and T_{sk} converge, a subject has reached tolerance limits (16). However, in this study, although T_{re} and T_{sk} convergence occurred in 8 of 9 subjects in the hot environment, subjects continued to exercise for a mean of 23 min to a tolerance time of 35.2 min. Thus, under our set of conditions, convergence does not appear to be an indicator of tolerance (15).

The results of the energy balance analysis clearly identify differences between the observed heat balance in vivo and those predicted from the model. The differences in total heat

production result from the use of various estimated work efficiencies (Q), i.e., values of either 5% or 20% (model default value) were used to convert metabolic energy to physical work. Partial explanations to account for some of the above discrepancies include: 1) the model failed to consider the energy required to raise the suit temperature (S_{suit}) calculated using the specific heat and the weight of the rubber suit as 28 kcal and (2) the model represents EVAP as 0 for the TAP, while observed EVAP likely overestimates EVAP due to drippage, making the actual term between 0 and 62 Kcal. If no heat loss can be attributed to either EVAP or S_{suit} , a required amount of air turnover (pumping) would need to remove as much as 95 kcal over the duration of the experiment (equal to an air exchange of 960 cf or 32 cfm). Thus, the range of observed and modeled values (kcal/30 min) for the TAP suit might be expressed as:

<u>S</u>	<u>(R+C)</u>	<u>EVAP</u>	<u>S_{suit}</u>	<u>$S_{\text{air exchange}}$</u>
203 to 108	35 to -30	0 to -62	0 to -28	0 to -95

This very preliminary analysis suggests the need for more definitive techniques in measuring the key variables involved in heat balance. Validation studies must then be undertaken in order to better resolve estimates of physiological thermal flux and energy balance with mathematical models of heat storage and laboratory observations.

Overall, the hot environment prompted a greater physiological adjustment across all ensembles. The relative magnitude of the thermal stress also depended on the type of ensemble worn, i.e., suits characterized by higher i_m/clo values (BDU and CDE) were much less physiologically stressful than the impermeable ensembles (TAP and RAIN). Body heat storage appeared to occur at a lower rate than expected, especially in the hot environments where $T_{\text{db}} > T_{\text{sk}}$ (which should make radiative heat loss negligible) and in trials where individuals wore the TAP and RAIN ensembles (which should have largely blocked evaporative heat loss). In these cases, most metabolic heat production should be stored as body heat, thus limiting work times to less than 15 min ($T_{\text{re}} > 39^\circ\text{C}$). Work times were 35.7 min for TAP and 33.6 min for RAIN in hot conditions, which again emphasizes the complex effect of clothing on heat balance in exercising individuals and the resulting difficulties in accurately predicting work tolerance time.

These results indicate that actual heat loss is much greater than the theoretical values estimated using standard equations which incorporate the clothing characteristics, clo and i_m/clo and environmental parameters observed. A much higher level of heat storage are predicted than actually occurs. Since the TAP suit is impermeable you would expect little heat loss due to evaporation. Surprisingly, measured evaporative heat loss is much higher than the zero predicted by the model. The TAP suit is loose fitting;

therefore, some evaporative cooling may be taking place at the skin inside the suit (23) or perhaps air is being "pumped" in and out of leg, arm, and neck openings providing additional evaporative cooling (which would be underestimated by our general heat balance equation).

In summary, this study evaluated the physiological stress imposed on exercising individuals by both environmental temperature and the insulation and permeability of protective clothing. It also compared these results with those from computer modeling of similar conditions. Obviously, the interaction between workload, clothing, and environment must be closely examined if safety from heat stress is to be improved without impacting the mission.

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TABLE 1. Final Physiological Values (\pm SEM)

TEMP	SUIT	TIME (MIN)	T _{re} (°C)	HR (bpm)	M _{sk} (°C)	SP (ml/min)	SE (ml/min)	SE/SP (%)
HOT	BDU	63.5 (3.8)°	38.7 (.13)	165 (7.3)	37.2 (.22)	23.9 (2.5)	9.5 (1.2)°	43.9 (5.9)°
HOT	CDE	56.0 (3.0)*	38.9 (.03)	174 (2.9)	37.8 (.06)+	23.2 (2.3)	6.9 (.40)+	31.9 (3.0)+
HOT	TAP	35.7 (2.1)*	38.6 (.13)	175 (4.4)	39.2 (.14)*	26.6 (2.3)	3.5 (.30)	13.8 (1.2)
HOT	RAIN	33.6 (1.4)*	38.5 (.12)	177 (3.7)	39.1 (.11)*	30.1 (2.8)	3.3 (.40)	11.2 (1.3)
WARM	BDU	70.3 (6.1)	38.2 (.15)	151 (9.4)	35.7 (.40)	17.7 (2.4)	8.3 (.58)	50.4 (3.9)
WARM	CDE	70.3 (6.8)+	38.9 (.10)	173 (3.9)	37.4 (.12)+	21.1 (2.6)	6.1 (.25)+	32.7 (4.1)+
WARM	TAP	49.8 (2.4)	38.8 (.12)	175 (4.6)	38.1 (.30)	23.8 (2.6)	2.8 (.22)	12.6 (1.3)
WARM	RAIN	43.7 (2.0)	38.6 (.14)	172 (4.8)	38.4 (.19)	26.3 (2.6)	2.6 (.50)	10.2 (1.9)

* values are significantly different ($p < .05$) from the WARM condition
+ values are significantly different ($p < .05$) from TAP and RAIN at the same temperature
o values are significantly different ($p < .05$) from (HOT) CDE, TAP, and RAIN conditions

TABLE 2. Comparison of Computer Modeling Results with Physiological Data
(kcal/30 min)

Trial	S (kcal/30 min)	Q (MR)	(R+C)	EVAP
TAP	108* =	.95# (210)*	-30#	-62*
TAP (modeled)	203* =	.80\$ (210)*	+35#	- 0*

Estimated Values, \$ Default Value, *Measured Values
S = heat storage, Q = 1 - work efficiency, MR = energy consumption / 30 minutes,
R + C = radiation + convection, EVAP = evaporation

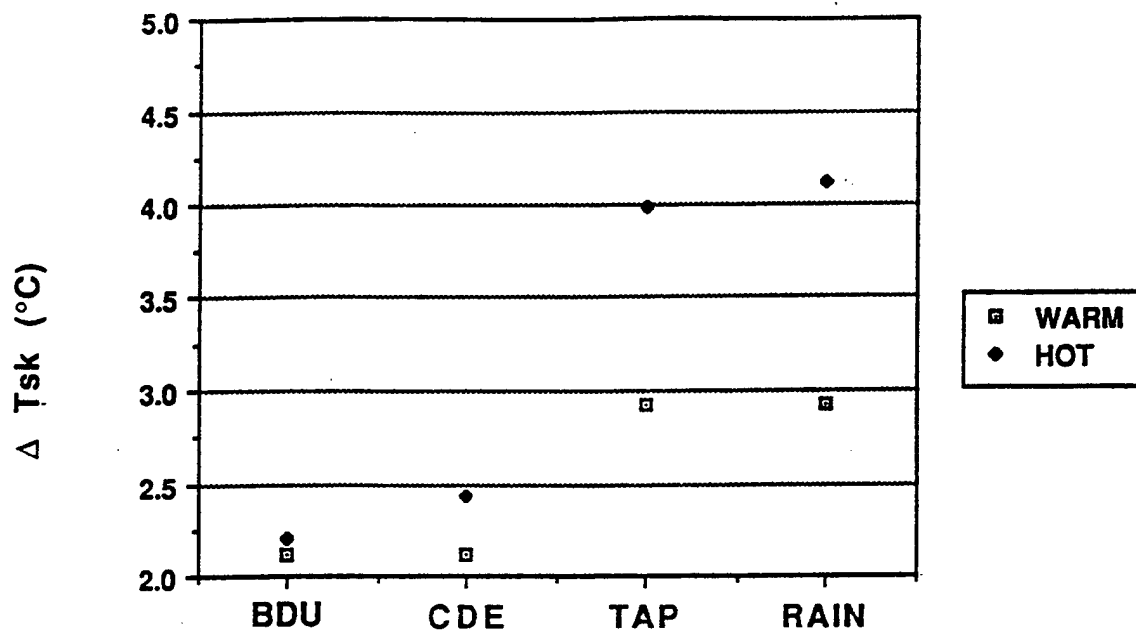


Figure 1. Delta increases in mean skin temperature (Tsk) at 30 minutes.

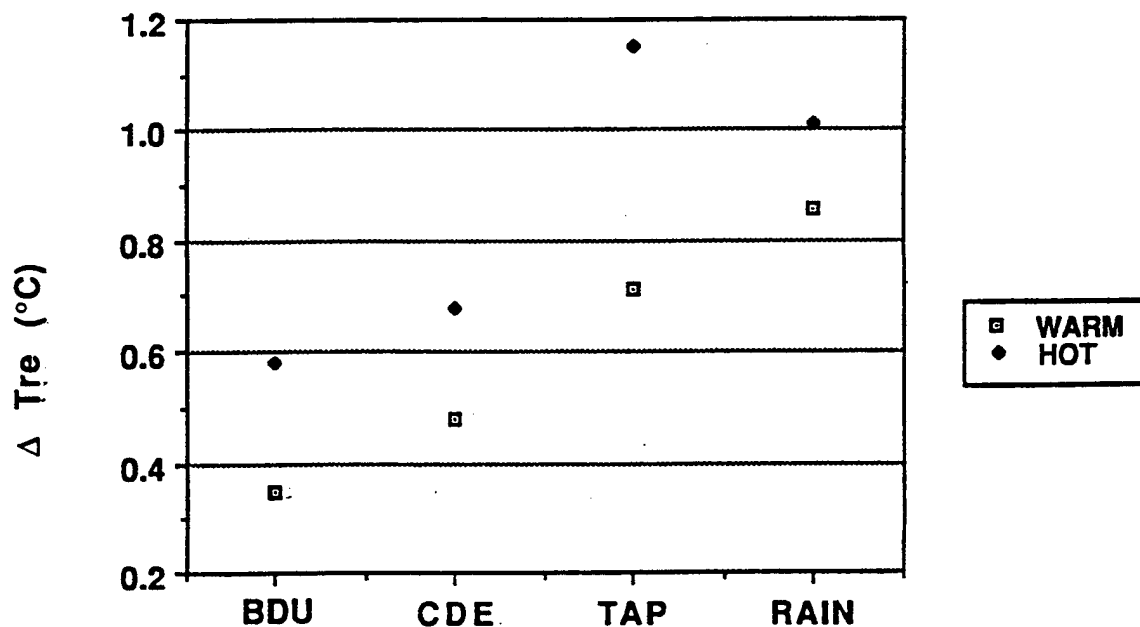


Figure 2. Delta increases in rectal temperature (Tre) at 30 minutes.

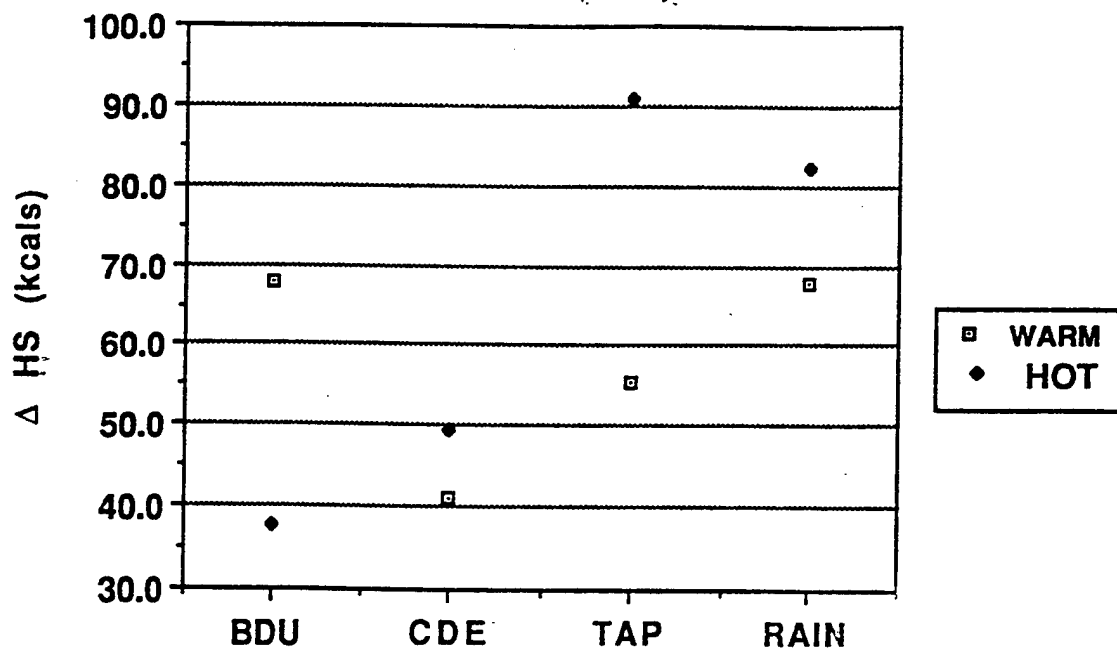


Figure 3. Delta increases in heat storage (HS) values at 30 minutes.

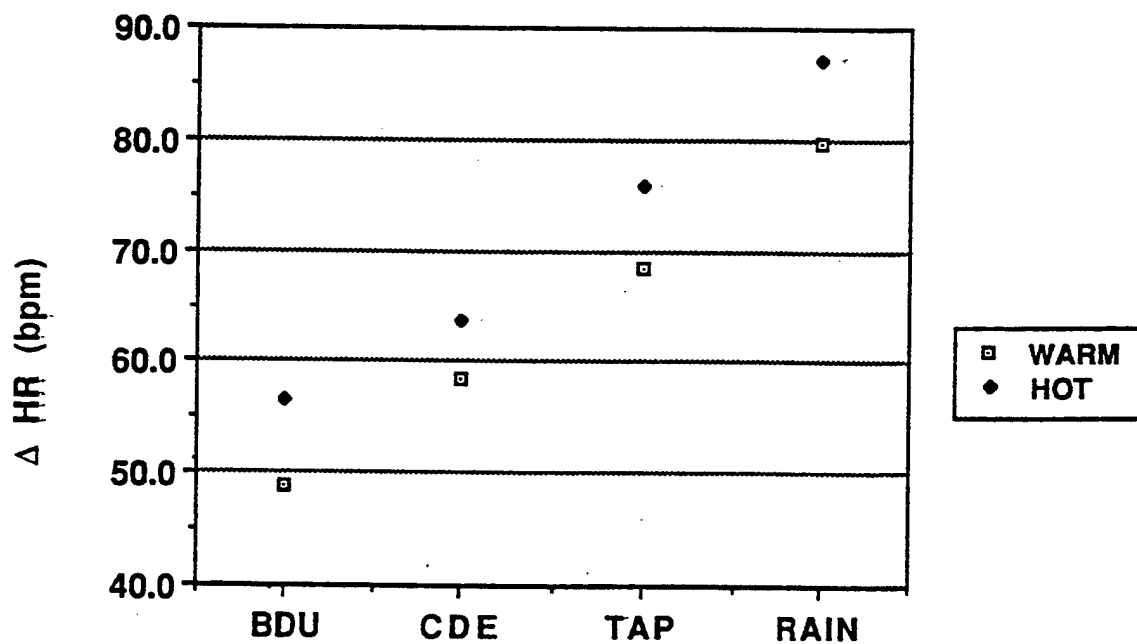


Figure 4. Delta increases in heart rate (HR) at 30 minutes.

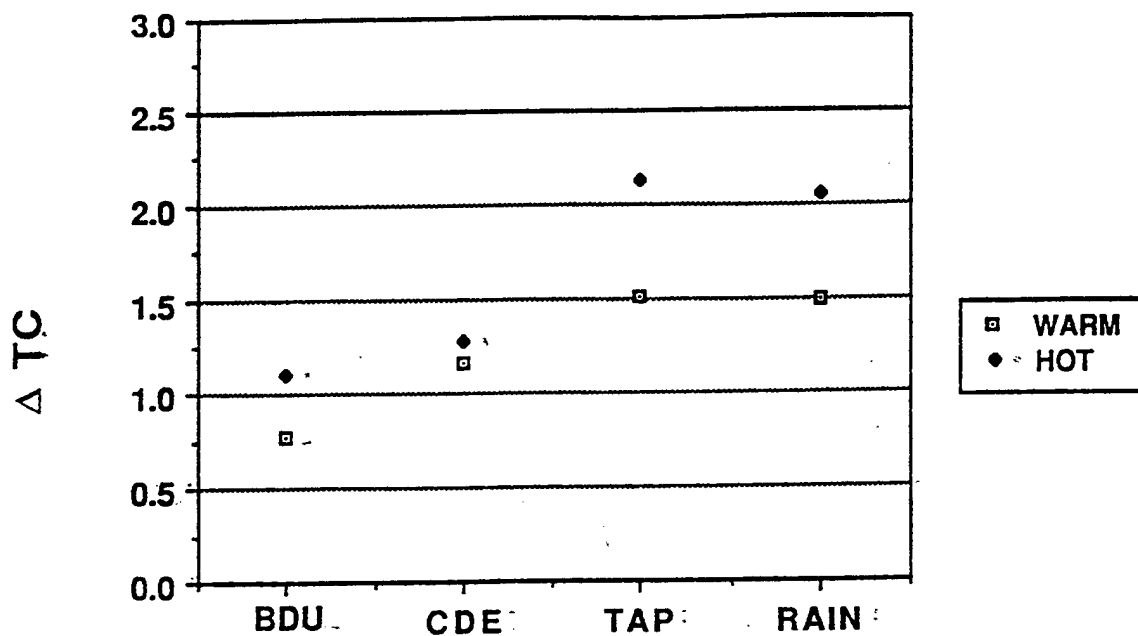


Figure 5. Delta increases in thermal comfort (TC) at 30 minutes.

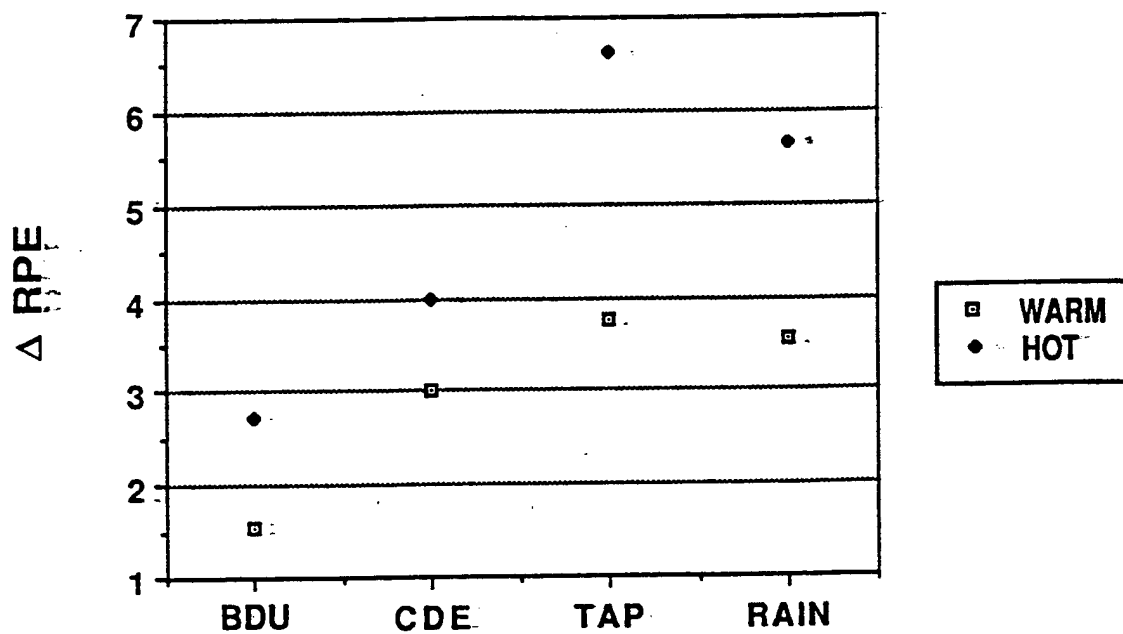


Figure 6. Delta increases in rated perceived exertion (RPE) at 30 minutes.